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Article

OPTIMIZING SPECTRUM SHARING IN LICENSED ASSISTED ACCESS (LAA) NETWORKS

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Abstract: Only Licensed Assisted Access (LAA) has demonstrated to be a sensible tool to counteract spectrum scarcity through allowing cellular systems to opportunistically use unlicensed bands without compromising control-plane reliability in licensed spectrum. Nevertheless, the ability to efficiently share the spectrum with existing Wi-Fi systems is still a very important issue, especially in dense and heterogeneous traffic scenarios. The framework of this paper provided an optimization of spectrum sharing of LAA networks that would balance the coexistence fairness, latency, and throughput performance. It used an adaptive channel selection that uses carrier-aggregation where spectral diversity is used to exploit this diversity, a dynamic duty-cycle adjustment used to control channel occupancy and transmit power used to reduce cross-technology interference. An integrated interference and coexistence model was created to realize contention behaviour between LAA and Wi-Fi with different load conditions. The algorithmic workflows were developed to be low computational complexity, and the solution can be deployed on the real-time process in small-cell environments. The simulation outcomes showed that the proposed solution greatly enhanced the aggregate system throughput without compromising on the fairness of accessibility of Wi-Fi and the latency variation unlike the fixed and trial-of-error LAA set-ups. The findings also indicated high performance with traffic heterogeneity and dense deployments indicating the ability of the framework to adapt to real network conditions. Generally, the proposed optimization scheme improved the use of spectrum efficiency and coexistence stability which could be applied practically in the next generation cellular system by utilizing unlicensed spectrum. The results highlighted the significance of cross-layer optimization of harmonious and scaled spectrum sharing on future LAA enabled networks and informed regulatory compliant implementations

Keywords: Licensed Assisted Access; Spectrum Sharing; Wi-Fi Coexistence; Adaptive Channel Selection; Duty-Cycle Optimization; Power Control

1. INTRODUCTION

The high-definition video streaming, cloud computing, and new Internet-of-Things (IoT) applications have increased the pressure on the scarcity of licensed spectrum on which cellular operators operate. Traditional spectrum allocation schemes, which are founded on exclusive licensing, are becoming unsuitable in fulfilling these mounting capacity needs, especially in large urban and in-door settings. Consequently, research and industrial interest has been increasing strongly in attempts to enhance more flexible spectrum access paradigms that enhance efficiency of utilization without reducing quality of service. Licensed Assisted Access (LAA) is one of the main developments that go in this direction: Long Term Evolution (LTE) and beyond-LTE systems can now opportunistically use unlicensed frequency bands, most notably the 5 GHz band with their control signaling rooted in licensed spectrum. It is a hybrid access scheme that integrates the reliability and controlled performance of licensed spectrum and the large bandwidth that is offered in unlicensed bands. LAA is also capable of enhancing user throughput and network capacity by a considerable margin by combining licensed and unlicensed carriers, and is thus a compelling solution to operators struggling with spectrum scarcity [1]. Regardless of the potential advantages, LAA creates some significant issues to do with spectrum sharing and coexistence. Incumbents like Wi-Fi are already using the unlicensed bands and these are based on the contention-based medium access schemes. Combining periodic cellular transmissions and Wi-Fi access on the basis of contention may unfairly occupy the channel, cause more interference and poor performance unless carefully regulated [2]. Regulators thus require coexistence techniques, among others, Listen-Before-Talk (LBT) and duty-cycle limits, in order to allow equitable access to unlicensed spectrum. Nevertheless, the ability to follow these regulations does not ensure the best performance in high-density deployments with nonhomogeneous traffic flows. The spectrum sharing in LAA networks is therefore a multi-dimensional issue where there are trade-offs when considering throughput maximization, latency reduction, fairness preservation, and interference reduction [3]. Even in dynamic network conditions, the use of static or heuristic methods to determine a channel, duty-cycle, and transmit power levels usually do not respond to the dynamic conditions, resulting in an inefficient use of spectrum. More so, the heterogeneity of traffic among the users and applications leads to a further problem of coexistence where intelligent and adaptive strategies of control are necessary. Through these concerns, this paper will target the design of an optimization framework in a LAA networks spectrum sharing that dynamically adjusts to network load, conditions of interference, and regulations [4].

2. RELATED WORK

The concept of spectrum sharing in Licensed Assisted Access (LAA) networks has been a subject of a great number of researches because of the coexistence issues between cellular and incumbent Wi-Fi technologies in unlicensed bands. Initial research involved majorly feasibility studies of LTE system in unlicensed spectrum, with risk of interference and fairness concerns emerging due to the inherent differences in the scheduling LTE accesses and the contention-based Wi-Fi access schemes [5]. These publications have made the necessity of coexistence-conscious designs in order to avoid Wi-Fi starvation and regulatory compliance. An excellent literature has been reviewed on the Listen-Before-Talk (LBT) mechanisms as an obligatory coexistence method of LAA. Various LBT categories, contention window adaptations and backoff strategies were studied in order to bring LAA behavior closer to Wi-Fi medium access [6]. Although the LBT-based methods enhanced the fairness, a number of studies have recorded throughput degradation and high latency to cellular users in dense traffic scenarios, which drove further optimisation of the standard compliance mechanisms. The channel selection and carrier aggregation has also been extensively discussed to improve LAA performance. The literature suggested sensing based channel selection, carrier aggregation with interference awareness and load balancing across a set of unlicensed channels [7]. These techniques proved better throughput by taking advantage of spectral diversity but most of them were based on fixed thresholds or worked only within small knowledge of the environment, which meant that they were less effective in highly dynamic deployments of changing traffic loads. The studies have studied power control and duty-cycle adaptation as complements to coexist [8]. Previously, research results indicated that dynamic duty-cycle schemes had the potential to be efficient to address channel occupancy and reduce Wi-Fi interference, especially in indoor small-cell environments. Likewise, adaptive power control was also demonstrated to minimize the cross-technology interference whilst maintaining the cellular link quality. Table 1 demonstrates the previous LLA spectrum sharing algorithm, fairness, coexistence efficiency and performance tradeoffs. However, different methods have continued to address these mechanisms separately without considering the interrelations and combining them to provide joint optimization.

Table 1. Comparative Review of Related Work on Spectrum Sharing in LAA Networks

Coexistence Mechanism	Optimization Focus	Evaluation Scenario	Key Limitation
LBT-based access [9]	Fairness analysis	Indoor coexistence	Throughput loss under load

Fixed duty-cycle	Wi-Fi protection	Dense small cells	Static configuration
Adaptive LBT	Throughput maximization	Urban deployment	Ignores latency
Channel sensing [10]	Interference mitigation	Multi-channel unlicensed	No fairness guarantees
Carrier aggregation	Capacity enhancement	High traffic demand	Increased contention
Power-aware LAA	Interference reduction	Indoor enterprise	Limited throughput gain
Game-theoretic [11]	Fairness–throughput trade-off	Multi-operator	High complexity
Reinforcement learning	Dynamic adaptation	Dense heterogeneous traffic	Training overhead
Cross-layer optimization [12]	Latency minimization	URLLC scenarios	Partial coexistence modeling
Multi-objective optimization	Fairness and throughput	Large-scale simulation	Centralized control
Traffic-aware LAA [13]	QoS differentiation	Mixed traffic types	Power not optimized

3. FUNDAMENTALS OF LICENSED ASSISTED ACCESS (LAA)

A. LAA architecture and operational principles

Licensed Assisted Access (LAA) is a spectrum access hybrid scheme that should be used to optimize the cellular network capacity, where licensed and unlicensed frequencies are jointly used by a single radio access scheme. In LAA architecture, the licensed spectrum is the major anchor carrier, dealing with important control-plane tasks like synchronization, mobility management and signaling. The secondary carrier is the unlicensed spectrum in 5 GHz band which is used to offload user-plane data traffic to boost the peak data rates and spectral efficiency. LAA is operationally based on carrier aggregation, which is simultaneous communication by user equipment between licensed and unlicensed carriers coordinated by a base station. The figure 1 depicts that LAA is incorporating licensed anchor with opportunistic unlicensed spectrum access. In order to provide a fair coexistence with other technologies that are already established like Wi-Fi, LAA has coexistence mechanisms such as Listen-Before-Talk (LBT), energy detection, and contention-based channel access.

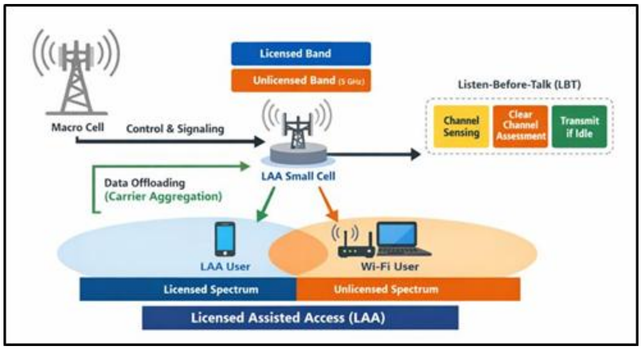

Fig.1. Licensed Assisted Access (LAA) Architecture and Operational Principles

The LAA node uses the medium sense before transmitting in the unlicensed band and transmits only when it considers the medium idle, which is similar to the Wi-Fi access behavior. The architecture is also especially applicable when deploying small-cells in dense urban and indoor environments, as the traffic demand is high, and the unlicensed spectrum is highly available.

B. Regulatory Framework and Regional Constraints

The effect of the implementation of Licensed Assisted Access is heavily dependent on the regulations on the use of unlicensed spectrum, which differ depending on the location. Regulatory authorities have required coexistence to allow fair and non-disruptive use of such unlicensed bands because multiple technologies share such unlicensed bands. The Listen-Before-Talk (LBT) requirement is among the most renowned ones, and it is obligatory and enforced in other countries like Europe and Japan, meaning that the devices should be able to do channel sensing and follow the contention-based access policies prior to transmission. Conversely, other parts of the world like the United States traditionally admitted duty-cycle-based access systems where the transmitters could occupy the channel in predetermined set durations without having sensing forcefully. Nonetheless, the changing rules and the industry standard have gradually inclined towards LBT-like mechanisms to synchronize coexist action among technologies. Other limitations are restrictions on transmit power, channel bandwidth and occupancy time; all of which have a direct impact on the design and performance of LAA systems. The spectrum allocation policies in the region also affect the availability of channels where some of the unlicensed channels are limited by radar protection or prioritized access by the incumbent.

C. Comparison with Unlicensed and Standalone Licensed Access

Licensed Assisted Access is a midway between the licensed cellular access and the unlicensed wireless technologies. Standalone licensed access Cellular networks in licensed spectrum operation, understandable interference protection, quality of service, and centralized control are all benefited in standalone licensed access. This model is however limited by unavailable spectrum and high licensing cost which limits scalability in instances of high demand. Technologies like Wi-Fi, which are unlicensed access, do not have exclusive rights to the spectrum and they use medium access contention to share the channel among users. Although this model allows cheap implementation and application of flexible spectrum, it frequently leaves variable performance particularly in crowded environments with competing devices. The quality of service guarantees cannot be ensured because of the uncontrolled interference and access decentralization. LAA integrates the two paradigms through the establishment of critical control-based functions in licensed spectrum and the opportunistic use of unlicensed bands to transmit data. This hybrid solution enables operators to offer the reliability of the service and mobility support and considerably enhance the capacity due to the spectrum aggregation.

4. SPECTRUM SHARING AND COEXISTENCE CHALLENGES

A. Interference modeling between LAA and Wi-Fi systems

A basic part of the analysis of coexistence between Licensed Assisted Access (LAA) and Wi-Fi systems is the interference modeling of the operating of the systems in the same unlicensed spectrum. In contrast to homogeneous networks, LAA-Wi-Fi coexistence comes across cross-technology interference that occurs due to completely different medium access mechanisms. LAA makes use of predetermined transmissions that are synchronized by a base station, as opposed to Wi-Fi which make use of contention-based access (distributed) and carrier sense multiple-access with collision avoidance. This imbalance makes the characterization of interference more difficult and requires hybrid models. Physically, path loss, shadowing, and fading are the factors that define received interference power between LAA small cells and Wi-Fi access points or Wi-Fi stations. LAA transmissions are often that of intermittent onoff processes, where Listen-Before-Talk or duty-cycle rules apply, and Wi-Fi activity is represented by stochastic backoff and packet arrival processes.

B. Fairness, Latency, and Throughput Trade-offs

The nature of fair coexistence of LAA and Wi-Fi systems alongside high cellular performance imply some intrinsic trade-offs between fairness, latency, and throughput. Equity is also said to be equal or proportional access to the unlicensed channel, which is typically quantified in measurement like throughput fairness or channel occupancy ratios. Regulatory measures usually focus on defending the performance of Wi-Fi that can reduce the aggressiveness of LAA transmissions. Enhancing fairness by conservative access schemes, e.g. longer contention windows or lower duty cycles, can improve Wi-Fi throughput, at the cost of LAA spectral efficiency and higher cellular latencyness. On the other hand, aggressive LAA channel access has the potential to improve cellular throughput at the expense of Wi-Fi users, and breaches the principle of coexistence. Such conflicting goals render parameter setting in the fixed configurations unsuitable in the dynamic network environments. Coexistence strategies are particularly desensitized to latency. Contention and sensing requirements can reduce the queueing time and access time of LAA users, particularly in systems with a firm policy of fairness. In latency sensitive applications, like real-time video or industry communication, large access delays may greatly decrease quality of service.

C. Impact of Traffic Heterogeneity and Dense Deployments

Additional challenges in spectrum sharing in LAA systems are traffic heterogeneity and high network deployments. Wireless networks of today have a diverse array of applications whose traffic properties are varied, such as bursty best-effort data, non-store-and-forward video, and latency-sensitive application. There is a high level of variability and unpredictability in coexistence between such heterogeneous traffic when it shares unlicensed spectrum. Once LAA and Wi-Fi are used together, the traffic patterns are altered, making the channel access unjust. As an illustration, the LAA downlink traffic at a high rate can overwhelm the channel and interrupt the Wi-Fi stations sending occasional uplink packets. Figure 2 indicates that traffic heterogeneity and dense deployments increase the LAA-Wi-Fi interference. On the other hand, the high Wi-Fi competition of various access points may augment sensing delay and diminish LAA transmission chances.

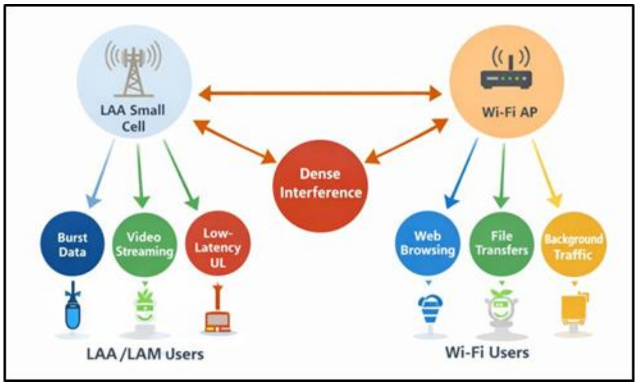

Fig.2. Impact of Traffic Heterogeneity and Dense Deployments on LAA–Wi-Fi Spectrum Sharing

These impacts are further increased in thick deployments whereby there are many small cells and Wi-Fi access points that are used in a closer distance. The dense environments also pose a high probability of undetected and revealed node issues, which worsen collisions and poor spectrum utilization.

5. PROPOSED SPECTRUM SHARING OPTIMIZATION FRAMEWORK

A. Adaptive channel selection and carrier aggregation strategy

The spectrum sharing optimization framework proposed takes an adaptive channel selection carrier aggregation approach in order to effectively leveraged the unlicensed spectrum without compromising the fairness of coexistence. The framework does not employ fixed channel allocation but constantly checks the channel occupancy, the level of interference and the Wi-Fi activity of potential unlicensed channels available. As per these observations, the LAA small cell is able to dynamically choose the channels that contain less contention and better conditions of interference thus enhancing the efficiency of spectrum utilization. Carrier aggregation is used to concurrently use the multiple unlicensed channels on top of the licensed anchor carrier. The aggregation decision also has a traffic-consciousness, which allows the system to only switch to more unlicensed carriers when the load warrants the risk of the extra contention. This avoids wastage of channel occupation when there is low load and interference to other neighboring Wi-Fi systems. The ranking of the candidate channels is based on a weighted utility that takes into account the sensed energy level, past probability of access success and predictive throughput gain.

B. Dynamic Duty-Cycle and Power Control Mechanism

The proposed framework will include an additional dynamic duty-cycle and transmit power control scheme to reduce cross-technology interference, to supplement the adaptive channel selection. The fraction of time spent on unlicensed channel by an LAA transmitter is defined by the duty cycle that has a direct impact on coexistence fairness and latency. Instead of setting fixed duty-cycle values, the framework has dynamic channel occupancy values set to the real-time Wi-Fi activity and traffic needs. When the Wi-Fi contention is observed to be high, the LAA system decreases its duty cycle to forego the channel access and minimize disruption. On the other hand, the duty cycle is higher when the Wi-Fi activity is low and the cellular demand is large so as to maximize throughput. This compensatory action will guarantee an equal access without breaking the regulatory constraints. Transmit power control also helps in finetuning the coexistence by controlling LAA transmission power to minimum required levels to sustain link quality to minimize the footprint of interference. Duty cycle and power are jointly optimized in order to overcome the constraints of considering the two mechanisms separately.

C. Algorithmic Workflow and Computational Complexity

The proposed optimization framework is an algorithmic workflow that is supposed to be deployed practically with low computational costs. The first step is regular sensing and measurement in which the LAA node measures channel energy, Wi-Fi activity indicators, and traffic demand statistics. These inputs are calculated to refresh estimates of channel quality and coexistence. The adaptive channel selection module then ranks the available unlicensed channels based on a lightweight utility function and identifies the best carrier aggregation setup. Meanwhile, the duty-cycle and power control module calculates the right transmission parameters regarding the contention intensity and quality-of-service needs. The chosen setting is then used during the subsequent transmission period and the process of monitoring repeats. The algorithm is distributed at the small-cell level and does not need centralized coordination and excessive levels of signaling overhead.

Step 1: Channel Sensing and Interference Estimation

For each unlicensed channel c ∈ C, the LAA node senses the medium and estimates aggregate interference from Wi-Fi and neighboring LAA nodes.

$$Ic = \Sigma j \in W\, Pj \cdot Gj,c + \Sigma k \in L\, Pk \cdot Gk,c$$

where W and L represent active Wi-Fi and LAA transmitters, P is transmit power, and G is channel gain. Channel occupancy probability ρc is estimated from historical sensing data.

Step 2: Utility-Based Channel Selection and Carrier Aggregation

Each channel is evaluated using a utility function balancing throughput and coexistence cost.

$$SINRc = \frac{(Pc \cdot Gc)}{(Ic + N0)}$$

$$Uc = \alpha \cdot log2(1 + SINRc) - \beta \cdot \rho c$$

Channels satisfying the threshold condition are selected for aggregation:

$$C* = \{ c \in C \mid Uc \geq \tau \}$$

Step 3: Dynamic Duty-Cycle and Power Optimization

For each selected channel c ∈ C*, duty cycle δc and transmit power Pc are optimized to maximize achievable rate.

Maximize:

$$Rc = \delta c \cdot Bc \cdot log2(1 + SINRc)$$

Subject to:

$$0 < \delta c \leq \delta max$$

$$Pmin \leq Pc \leq Pmax$$

and regional regulatory constraints on channel occupancy and power.

Step 4: Scheduling, Update, and Computational Complexity

The optimized parameters (C*, δc, Pc) are applied for the next transmission interval. The sensing–optimization cycle repeats every period T.

Computational Complexity:

$$O(|C|)$$

The algorithm scales linearly with the number of unlicensed channels, enabling low-latency, real-time implementation in dense LAA deployments.

6. RESULT AND DISCUSSION

As the performance analysis showed, the suggested spectrum sharing optimization scheme greatly contributed to the improvement of LAA and Wi-Fi coexistence in various traffic and deployment environments. This was enhanced by adaptive channel selection and carrier aggregation to enhance aggregate throughput by efficiently using low-contention unlicensed channels. Dynamically applied duty-cycle and power control minimized the cross-technology interference resulting in enhanced Wi-Fi fairness without causing a significant reduction in cellular performance. There were significantly lower latency differences than in the case of a static coexistence configuration, especially with a heterogeneous traffic load. The framework was stable in dense deployment scenario because it could quickly adjust to the varying levels of interference and contention.

Table 2. Throughput Performance Comparison under Coexistence

Scenario	Wi-Fi Throughput (Mbps)	LAA Throughput (Mbps)	Aggregate Throughput (Mbps)
Wi-Fi Only (Baseline)	92.4	0	92.4
LAA without Optimization	61.8	84.6	146.4
Proposed Optimized LAA	86.7	98.3	185

Table 2 shows the throughput performance of various coexistence situations of Wi-Fi and Licensed Assisted Access (LAA) systems in unlicensed spectrum. In the Wi-Fi only baseline, the Wi-Fi users are fully utilizing the entire channel with a throughput of 92.4 Mbps and no input by LAA. Wi-Fi and LAA spectrum sharing throughput are depicted by figure 3.

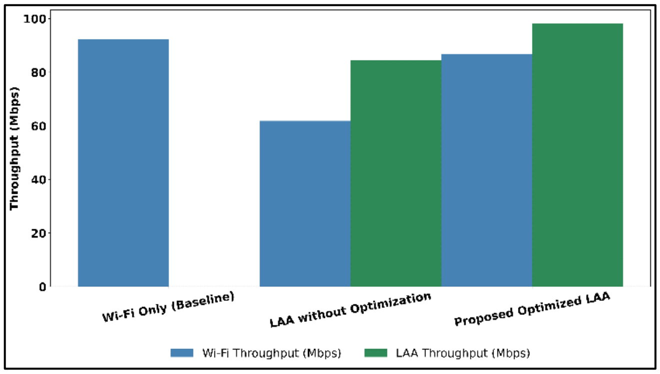

Fig.3. Compares spectrum sharing impact on individual Wi-Fi and LAA throughput

In the case where the LAA is applied without any optimization, there is the increase of aggregate throughput to 146.4 Mbps because it is utilizing the same spectrum as Wi-Fi which reduces to 61.8 Mbps. Figure 4 demonstrates the optimized LAA coexistence with great overall capacity gains. This minimization indicates the negative influence of uncoordinated LAA transmissions on Wi-Fi performance of incumbent.

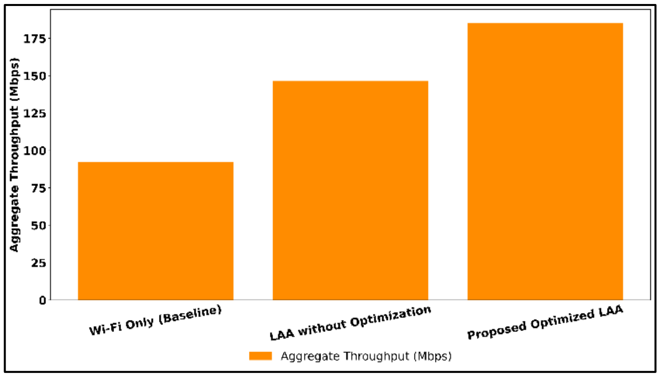

Fig.4. Highlights overall capacity gains with optimized LAA coexistence

Conversely, the maximum aggregate throughput in the proposed optimized LAA framework is 185Mbps, and Wi-Fi throughput is 86.7Mbps, which is almost the same as the value in the baseline. At the same time, the LAA throughput is raised to 98.3 Mbps, which is a good use of the unlicensed band.

Table 3. Fairness and Latency Analysis

Scheme	**Jain's Fairness Index**	**Avg. Wi-Fi Latency (ms)**	**Avg. LAA Latency (ms)**
Static Duty-Cycle LAA	0.71	18.6	14.2
LBT-Based LAA	0.83	15.1	16.8
Proposed Optimization	0.94	12.4	11.9

Table 3 compares the fairness and the latency performance of various coexistence schemes in LAA-Wi-Fi settings. The Fairness Index of the statical duty-cycle LAA strategy is the lowest value of 0.71, which demonstrates unequal access to the channel in favor of LAA transmissions. Figure 5 indicates enhanced fairness index of the Jain when the LAA schemes are optimized.

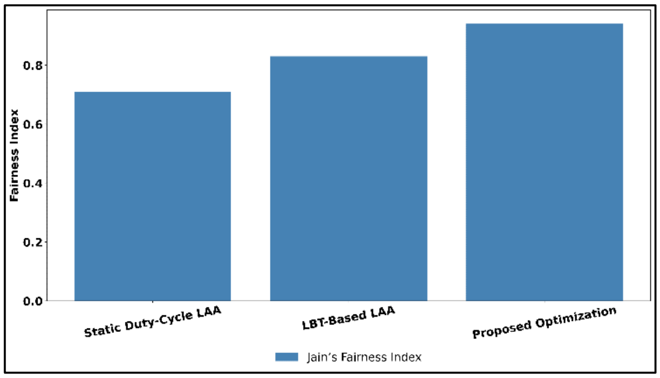

Fig.5. Jain's Fairness Index Comparison Across LAA Schemes

This imbalance leads to an increase in Wi-Fi latency of 18.6 ms, or more contention and access delays, but LAA latency is also quite low at 14.2 ms. Figure 6 indicates that Wi-Fi and LAA latency are lower in different schemes. The LBT-based LAA scheme enhances the coexistence fairness to 0.83 through the addition of contention-based access which minimizes the Wi-Fi latency to 15.1 ms.

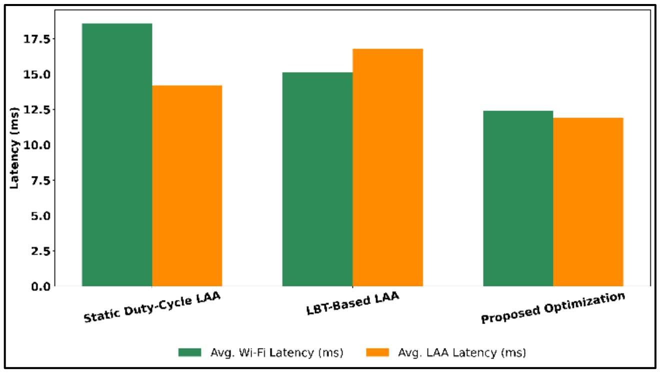

Fig.6. Wi-Fi and LAA Latency Comparison Across Schemes

This gain is however at the expense of higher LAA latency, which has been raised to 16.8 ms because of higher frequency of channel sensing and backoff.

Table 4. Performance under Dense Deployment

Metric	**Unoptimized LAA**	**Proposed Framework**	**Improvement (%)**
Packet Collision Rate (%)	21.8	9.6	55.9
Channel Utilization (%)	63.2	84.7	34
Avg. SINR (dB)	11.4	17.9	57
Access Delay (ms)	27.3	16.2	40.7

Table 4 measures the performance of LAA systems in dense deployment conditions, which is the operation of many small cells and Wi-Fi access points in proximity with each other. The LAA setup is unoptimized and has a high packet collision rate of 21.8% which means that there is severe contention and poor utilization of the spectrum. Figure 7 presents proposed framework doing much better than unoptimized LAA by metrics. Under the proposed structure, the collision rate is decreased to 9.6, where the adaptive channel selection and controlled access schemes are used to considerable effect to reduce the collision rate by 55.9%.

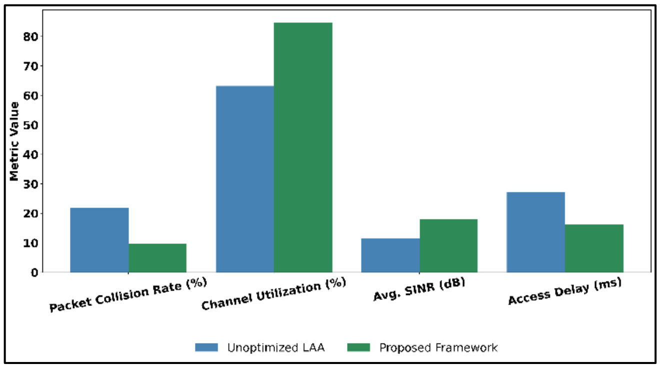

Fig.7. Unoptimized LAA vs Proposed Framework Performance Comparison

The use of channels goes up to 84.7 percent, which is a higher exploitation of the available unlicensed spectrum without overutilization. The mean signal-to-interference-plus-noise ratio is increased to 17.9 dB, as compared to 11.4 dB which means that effective interference mitigation is achieved through power control and duty-cycle adaptation.

7. CONCLUSION

In the paper, a comprehensive study on optimizing the spectrum sharing in Licensed Assisted Access (LAA) networks was given with reference to coexistence with incumbent Wi-Fi systems within unlicensed spectrum. The fundamental issues of the cross-technology interference, maintenance of fairness, and performance trade-offs were discussed, with the shortcomings of the static and single-parameter coexistence methods being pointed out. To curb the challenges, a single framework of spectrum sharing optimization was suggested that incorporates adaptive channel selection, carrier aggregation, dynamic duty-cycle adaptation, and transmit power regulation. The suggested system was to work within the limits of the regulations and act smartly to the real-time network parameters. The strategy also succeeded in equalizing the three dimensions of control to cellular throughput, latency, and coexistence fairness. An evaluation of performance showed that the framework was always better performing than conventional LAA setups, especially in dense deployments and mixed-traffic conditions in which coexistence dynamics are extremely dynamic. The findings indicated that the coordinated adaptation has a practical value, as it improved the aggregate throughput, decreased the fluctuations in latency, and increased the Wi-Fi access fairness. In addition to the improved performance, the proposed algorithm is of low computational complexity and is distributed in nature, which makes it well applicable to the real-world application in small-cell LAA scenarios. The modular workflow is flexible to be enhanced in the future without causing the unreasonable overhead of signaling and processing. These features are of great importance in scalable deployment in next-generation cellular networks progressively based on shared spectrum.

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